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ORIGINAL RESEARCH

ANALYSIS OF TIMING OF SECONDARY ACL INJURY IN PROFESSIONAL ATHLETES DOES NOT SUPPORT GAME TIMING OR SEASON TIMING AS A CONTRIBUTOR TO INJURY RISK

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ABSTRACT

Background: Anterior cruciate ligament (ACL) injuries are a common cause of time loss in sports. Approximately one-third of ACL reconstructed athletes who return to sport suffer secondary injury. The presence of fatigue during athletic performance has been hypothesized to increase susceptibility to ACL injury. However, the relative role of fatigue in secondary ACL failures remains unexplored.

Purpose: To assess how time elapsed within a game and within a season associate with secondary ACL injury occurrence in international professional athletes and American collegiate athletes**.**

Study Design: Retrospective cohort analysis

Methods: The public domain was searched for secondary ACL injuries that occurred during competitive matches between 2000-2018. Demographics (age, height, weight), side of injury, type of injury (contact, noncontact), and timing of injury within competition and within season were determined for each case.

Results: Sixty-seven secondary ACL injuries were identified. Within-game, there were no differences in the distribution of ACL injures across each quarter of game time ($p = 0.284$). This was consistent between sport ($p = 0.120$-0.448). Within-season, there were no differences in the distribution of secondary ACL injures across each quarter of the season ($p = 0.491$). This was again consistent between sport ($p = 0.151$-0.872). Relative risk was not found to be significantly greater for any combination of season and game.

Conclusion: The results of the current study indicate that the occurrences of secondary ACL injuries were equally distributed with respect to in-game and in-season timing. Both in-game and in-season timing were not significantly different across each individual sport examined. These results implicate that overall there is not an association between fatigue and secondary ACL injury occurrence in professional athletes.

Level of Evidence: 3

Keywords: anterior cruciate ligament injury, fatigue, knee, professional athletes, sports injury

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Acknowledgements: We acknowledge grant funding from NIH R01-AR055563, NIH K12-HD065987, and the Jiangsu Health International Exchange Program (JSH-2018-004).

Conflict of Interest: There are no conflicts of interest of financial relationships to disclose for any of the authors in preparation of this manuscript.

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DOI: 10.26603/ijspt20200254

INTRODUCTION

Anterior cruciate ligament (ACL) injury is a common sports injury with an estimate in excess of 200,000 annual incidents per year in the United States.[1,2] These injuries are particularly prevalent among young athletes, between the ages of 15 and 25,[3] and females, who are 2-10 times more likely to experience ACL failure than their male counterparts.[4-7] It is estimated that ACL injuries account for 14-17% of all sports-related lower extremity injuries.[8,9] Athletes who desire to return to their preinjury activities typically undergo ACL reconstructions (ACLR) to re-establish mechanical knee stability.[10] However, these ACLR's fail to fully restore the mechanics of the native knee,[11] and between 16-33% of athletes who return to their previous level of sport with ACLR suffer additional ACL ruptures, known as a secondary injuries.[12-14]

Secondary ACL injures can entail re-tear of the previously injured ACL or subsequent injury to the contralateral ACL.[15] A retrospective cohort study that evaluated 17,436 ACLR's found that 4.9% experienced ipsilateral ACL re-injury and 4.2% experienced contralateral ACL injury within five years.[16] However, this study population was limited in that athletic activity and subsequent return to athletic activity were not tracked. The higher physical demands on professional athletes put them at a greater risk of injury than the general population;[17] therefore, higher rates of injury are expected, and have been observed, in athletic-specific populations that return to sport after ACLR.[12-14] In addition, athletic exposures during competitive game scenarios present considerably higher risk for ACL injury than training sessions.[18] Athletes involved in competitive sports activities prior to surgery have an increased risk of revision ACL surgery compared with those not involved in competitive sports.[19] Therefore, professional athletes who return to high levels of sport from ACL injuries are highly susceptible to a second ACL injury.[14,20,21]

Despite growing interest in the relationship between fatigue and ACL injury, the nature of this association, especially with relation to secondary ACL injuries in professional athletes, remains inconclusive. Athletes who participate in high-impact, cutting, and pivoting sports are at risk of sustaining multiple ACL injuries.[22] In general, professional athletes are assumed to be more fatigued in the second half of a game and the second half of a season than in the first halves, respectively. However, this is not a comprehensive interpretation as fatigue can be generated by a sudden spike of activity within a particular game or as a neuromuscular response to cumulative playing time over an extended period, both of which may increase vulnerability to injury.[23] Several authors have purported that fatigue propagates deleterious biomechanics as fatigue onset has been associated with increased knee abduction angles and moments,[24-28] decreased range of flexion excursion,[23,25,26,28-30] increased asymmetry in frontal and sagittal plane knee moments,[30] delayed hamstrings neuromuscular activation,[31,32] and increased vertical ground reaction and knee joint forces.[23,30,33-35] These changes would be indicative of stiffer landing mechanics and decreased energy absorption that correspond with increased ACL injury risk.[23,29] However, these principles are not universally accepted as contrarian findings have identified that extended exercise and fatigue increase flexion,[24,35-37] increase muscle activation,[38] do not influence frontal plane mechanics,[23,39] decrease vertical ground reaction forces,[40] and decrease load on the ACL.[41] Collectively, fatigue-related findings have exhibited limited congruency relative to motion mechanics;[23,42] thus, it remains inconclusive as to how fatigue influences injury incidence within athletic exposures.

Therefore, the purpose of this investigation was to assess how time elapsed within a game and within a season associate with secondary ACL injury occurrence in international professional athletes and American collegiate athletes. The hypothesis tested was that the occurrence of secondary ACL injuries would be equally distributed with respect to in-game and in-season timing. It was further hypothesized that in-game and in-season timing would exhibit differences between sports.

METHODS

For this investigation, an internet search was conducted in order to identify professional and American collegiate athletes who had suffered a public and video-documented secondary ACL injury in a game, match, or contest between 2000 - 2018. Game

scenario ACL injuries were selected for analysis because it allowed the raters to determine the precise timing of injury occurrence and because competitive game scenarios expose a considerably higher risk of ACL injury than training.[18] Secondary ACL injures were classified as any additional ACL injuries that occurred after the date of an athlete's primary ACL injury, and included ipsilateral injuries of an ACLR graft as well as additional ACL injuries contralateral to a previously-injured ACL. The search engines used in this investigation were the news article feature on Google, ESPN, and the ACL Recovery Club's Twitter feed. Two investigators used the search terms "ACL injury" and "ACL injured" coupled with the major national sports leagues (NFL, NBA, AFL, etc.) to find documented instances of ACL ruptures. For each ACL injury identified, that athlete was subsequently searched for history of prior ACL injury. Inclusionary criteria were restricted to those secondary ACL injuries that occurred within a game, such that the precise time of injury could be documented. Athlete demographics (age, height, weight), side of injury (contralateral, re-tear), and type of injury (contact, noncontact) were also recorded. Type of injury was determined either from recorded video of the injury event and visual observation of whether a direct blow of force was delivered to the knee, or from interpretation of written description. Language such as "when landing" or "while making a cut" was interpreted as noncontact, while language such as "was hit at the knee" or "collided with another player" was interpreted as contact. The injury data search was concluded December 2018.

Once an athlete was determined to have sustained multiple ACL injuries, their secondary injuries were investigated to discern in what game of the season and what time point within the game their injury occurred. Any injury event where these two data points could not be extracted was excluded from analysis. Dependent variables included tear location, tear type, number of games played, percentage of season completed, quarter of the game at time of injury, and percentage of game completed prior to injury. For sports that were not pre-divided into quarters based on standard regulations, each quarter of the competition was determined by a percentage of the total time elapsed on the game clock or total innings completed. Student t-tests were used to assess demographic differences between tear types and sports played ($\alpha < 0.05$). Bonferroni correction for multiple comparisons were applied when differences between sports were assessed. Sport specific differences were only assessed for those sports that expressed a minimum of seven secondary ACL tears (American football, Australian football, basketball, soccer). Chi-Squared tests of the distribution ($\alpha < 0.05$) were used to determine if ACL injuries were evenly dispersed within-game and within-season (based on quarters). A relative risk was used to assess the risk for second ACL injury between half-of-season and half-of-game.

RESULTS

A total of 67 secondary ACL injuries (63 males, 4 females) were identified in professional athletes that participated in Australian Rules Football (AFL), Baseball, Basketball, American Football (Football), Hockey, Rugby, or Soccer at the time of injury (Table 1). Of the secondary injuries documented, 55% were re-tears and 93% occurred in noncontact scenarios. For secondary ACL athletes, the mean age was 26.4 $\pm$ 4.6 years, height was 188 $\pm$ 9 cm, and weight was 98.3 $\pm$ 18.5 kg. There were no differences in age or weight between contralateral and ipsilateral injury presentations ($p \geq 0.569$); however, athletes who suffered re-tears were generally 4 cm taller than those who suffered contralateral injury (Pp = 0.033). There were an insufficient number of contact-based secondary ACL injuries to assess demographic differences between contact and noncontact tears. There were also significant demographic differences between sport as basketball athletes with secondary ACL tears were 10 $\pm$ 4 cm taller than soccer athletes ($p = 0.014$) and 8 $\pm$ 3 cm taller than American football athletes ($p = 0.009$). Basketball athletes also weighed 16.5 $\pm$ 8.0 kg more than soccer athletes, but 12.8 $\pm$ 5.9 kg less than American football athletes ($p = 0.035$) who were 17.2 $\pm$ 5.4 kg and 29.3 $\pm$ 6.8 kg heavier than Australian football ($p < 0.001$) and soccer athletes ($p = 0.002$), respectively.

Within-game there were no differences in the distribution of ACL injuries across each quarter of a game ($p = 0.284$). These results remained unchanged within each individual sport ($p = 0.120$-0.448, Figure 1). Timing of second ACL injury within-game

Table 1. *Secondary ACL ruptures identified in professional athletes by sport and type of tear. Data is presented as number of injuries (percentage of population) for the sport specified in each column.*

	AFL	Baseball	Basketball	Football	Hockey	Rugby	Soccer	Total
Tear Location								
Re-Tear	7 (50)	2 (100)	7 (64)	17 (55)	0 (0)	0 (0)	4 (57)	37 (55)
Contralateral	6 (43)	0 (0)	4 (36)	13 (42)	1 (100)	1 (100)	3 (43)	28 (42)
Unknown	1 (7)	0 (0)	0 (0)	1 (3)	0 (0)	0 (0)	0 (0)	2 (3)
Tear Type								
Non-contact	14 (100)	2 (100)	10 (91)	28 (90)	1 (100)	1 (100)	6 (86)	62 (93)
Contact	0 (0)	0 (0)	0 (0)	2 (7)	0 (0)	0 (0)	1 (14)	3 (4)
Unknown	0 (0)	0 (0)	1 (9)	1 (3)	0 (0)	0 (0)	0 (0)	2 (3)
Quarter of Game								
1st	5 (36)	0 (0)	1 (9)	11 (35)	0 (0)	1 (100)	2 (29)	20 (30)
2nd	5 (36)	0 (0)	6 (55)	5 (16)	0 (0)	0 (0)	4 (57)	20 (30)
3rd	2 (14)	2 (100)	3 (27)	6 (19)	0 (0)	0 (0)	0 (0)	13 (19)
4th	2 (14)	0 (0)	1 (9)	9 (29)	1 (100)	0 (0)	1 (14)	14 (21)
Quarter of Season								
1st	6 (43)	0 (0)	1 (9)	11 (35)	0 (0)	1 (100)	0 (0)	19 (28)
2nd	2 (14)	0 (0)	5 (45)	7 (23)	0 (0)	0 (0)	2 (29)	16 (23)
3rd	1 (7)	1 (50)	3 (27)	4 (13)	1 (100)	0 (0)	2 (29)	12 (18)
4th	5 (36)	1 (50)	2(18)	9 (29)	0 (0)	0 (0)	3 (42)	21 (31)

AFL= Australian Rules Football

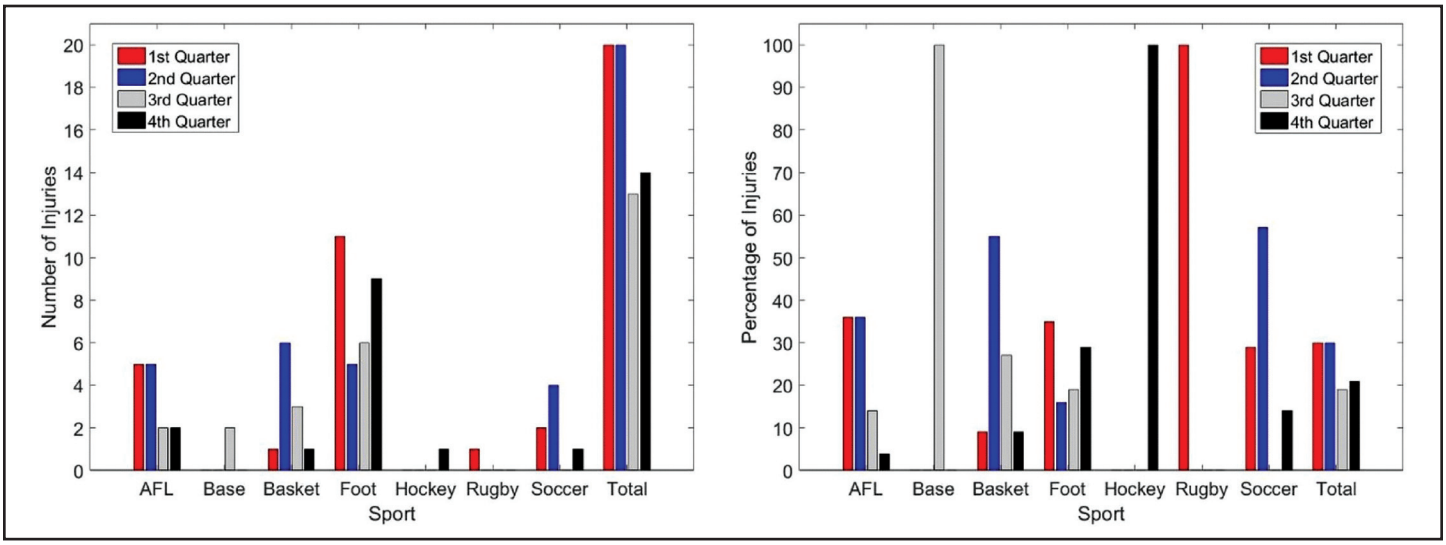

Figure 1. *(A) Absolute number of ACL injuries that occurred within each quarter of a game separated by sport. (B) Percentage of ACL injuries that occurred within each quarter of a game separated by sport.*

and within-season was consistent between injury type (p = 0.364 & 0.407; Table 2) and sport played (p = 0.736 & 0.555). Within-season, there were no differences in the distribution of second ACL injures across each quarter of the season (p = 0.491, Figure 2). These results remained unchanged within each individual sport (p = 0.151-0.872). Timing of second ACL injury within-game and within-season was consistent between injury type (p = 0.728 & 0.487) and sport played (p = 0.491 & 0.679). Relative risk between half-of-season and half-of-game where second ACL injury occurred was not found to be significantly greater for any single category (Table 3).

DISCUSSION

The objective of this investigation was to assess how time elapsed within a game and within a season associate with secondary ACL injury occurrence in professional and American collegiate athletes. The primary hypothesis that second injury would be equally distributed across time points in game and across a sports season was supported by the lack of difference in injury incidence recorded between each quarter of athletic competition. The incidence distribution observed in the present investigation supports a prior meta-analysis that found no effect of season or game time on the occurrence of ACL, groin, or hamstring injuries.[40] Additional prior reviews also found inconclusive effects of fatigue on motion mechanics.[23,42] Inconsistent behavioral adaptations from fatigue would consequently not be expected to bias injury incidence toward a particular timing aspect of a game or season. Indeed a soccer-specific investigation found that 17 of 78 (22%) ACL injuries occurred within 15 minutes of kickoff (17% of game time).[18] This indicates a relatively even distribution of injury incidence compared to the time elapsed and echoes the findings of the present investigation.

The demographic data of this study, suggest that a higher center of gravity is more likely to affect the involved side as athletes with ipsilateral re-injury were 4 cm taller than athletes with contralateral tears. Indeed, taller center of mass has been observed in landings with larger vertical ground reaction forces, frontal plane angles, and frontal plane moments,[43,44] all of which are known risk factors associated with ACL injury.[45] In addition, the differences in athlete height and weight observed between sports may be

Table 2. *Timing of secondary ACL rupture by sport (with standard deviations where multiple subjects were observed).*

Sport	Games Played	Percentage of Season	Quarter Injury Occurred	Percentage of Game
AFL	9.1 (8.5)	46.8 (39.1)	2.1 (1.7)	41.8 (27.3)
Baseball	134.5 (30.4)	83.1 (18.7)	3.0 (0.0)	66.7 (0.0)
Basketball	33.6 (22.6)	55.0 (25.5)	2.4 (0.8)	50.1 (19.4)
Football	76.9 (5.6)	46.6 (38.0)	2.4 (1.3)	48.5 (34.3)
Hockey	47	57.3	4	99.2
Rugby	4	16.7	1	3.9
Soccer	27.6 (10.6)	65.9 (17.2)	1.4 (1.1)	38.2 (21.1)
Total	18.2 (26.1)	50.8 (34.3)	2.3 (1.2)	47.0 (29.6)

AFL= Australian Rules Football

Table 3. *Relative risk for groups.*

Condition	Relative Risk	Lower 95%	Upper 95%
1st half game, 1st half season VS. 1st half game, 2nd half season	1.23	0.82	1.83
1st half game, 2nd half season VS. 1st half game, 1st half season	0.82	0.55	1.22
2nd half game, 1st half season VS. 2nd half game, 2nd half season	0.72	0.38	1.36
2nd half game, 2nd half season VS. 2nd half game, 1st half season	1.39	0.74	2.61

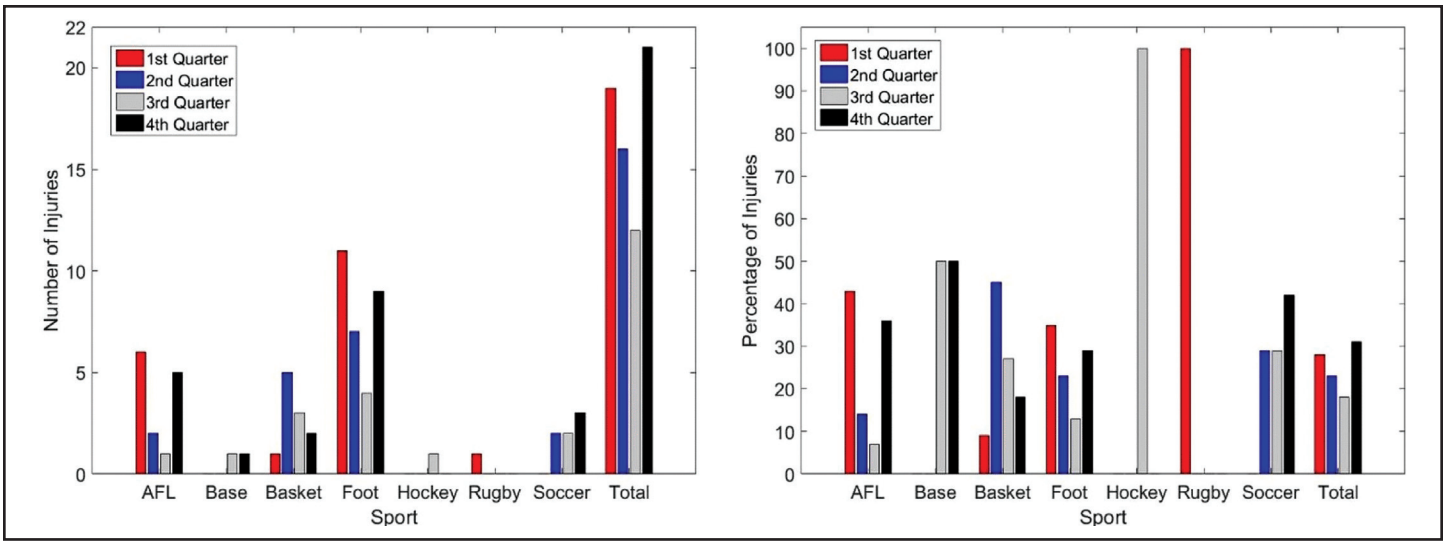

Figure 2. *(A) Absolute number of ACL injuries that occurred within each quarter of a season separated by sport. (B) Percentage of ACL injuries that occurred within each quarter of a season separated by sport.*

related to center of gravity and balance control, or to sport-specific demands. Therefore, these demographic data may have limited clinical significance, or at least necessitate investigation with a larger dataset to results with greater power.

Younger age and a return to high levels of activity following primary ACLR are salient factors associated with secondary ACL injury.[14] Professional athletes exhibit higher levels of activity than the general population and often experience sport-specific fatigued conditions due to year-round participation in workouts, practices and games.[46] Fatigue and overtraining may compromise coordination as well as athlete awareness, which can subsequently increase the risk of ACL injury.[47] Physical fatigue has been tied to mental (i.e. cognitive) fatigue as it might influence one's abilities to focus on important cues around him/her, compromise cognitive processing, and impair decision-making.[42,48,49] Decreased cognitive function following concussion has been associated with increased ACL injury incidence;[50] therefore, cognitive fatigue that results from physical fatigue could also influence ACL incidence rates. However, such a concept was not examined in the present study.

Game-context athletic exposures generate considerably higher ACL injury incidence rates than training situations.[18] Athletes may experience fatigue as a results of a sudden activity spike during the game or as neuromuscular fatigue because of extended playing time.[23] For athletes with prior history of ACL reconstruction, decreases in movement quality were noted with the onset of fatigue, while no such changes were documented in healthy control subjects.[51] However, if these deleterious motion changes occurred in the present cohort, they did not influence a biasing of ACL occurrence relative to game time or season time elapsed.

Following the onset of fatigue, athletes demonstrate greater vertical ground reaction forces (vGRFs) during landing, regardless of sex.[52] As noted, increased frontal plane hip and knee moments and angles, as well as increased hip and knee internal rotation, have been documented as side-effects of fatigue in some investigations.[53] Each of these factors are a component of dynamic valgus which is associated with increased risk of non-contact ACL injury *in vivo*[45,54] and increased ACL loading *in vitro*.[55-57] Furthermore, as the body absorbs vGRFs during movement, if neuromuscular control surrounding the joints is altered due to fatigue, it may increase ligament susceptibility to rupture.[58] The present study was unable to estimate specific kinetic and kinematic biomechanical variables during documented injury events. Therefore, the authors were unable to document whether these traits were observed in this cohort of professional athletes.

In accordance with the present results, study of male youth elite soccer players showed that soccer-specific fatigue did not increase the risk of ACL or hamstring injury.[59] A second soccer-specific study echoed these findings in that no consistent relationship was identified between fatigue, playing time, and injury.[18] A third cross-sectional study examined quadriceps muscle fatigue in 17 high-performance soccer players between 5.5 and 7 months after ACL reconstruction.[17] The results showed no significant difference between involved and uninvolved limbs regarding local muscle fatigue. As ACL loading and injuries are multi-factorial events across multiple planes of motion,[45,56,57,60,61] fatigue as a single factor, may not be sufficient to reliably induce secondary ACL injury in professional athletes. In addition, as professional athletes consistently participate in training and competition, they may be better adapted to functional performance under fatigued conditions than the general population. However, further investigation would be required to confirm or refute this theory.

The primary limitation of the present study was that individual participant fatigue was not objectively measured or controlled for. As injury incidence was documented from the public domain, there was no reliable or accurate method available to document individual participant fatigue at the time of injury occurrence. It was generally assumed that as game time and season duration progressed, an athlete's potential level of fatigue would subsequently increase. Based on the reasonable consideration that professional athletes are more overall fatigued in the second half of a game and the second half of a season than in the first half of the game and the first half of the season, only the timing of secondary ACL injury that occurred during the game and the season was analyzed. However, due to large variability in substitution patterns, relative use patterns, positional responsibilities, and individual fitness

associated with professional sports, the assumption of fatigue onset is not comprehensive or quantifiable. Accordingly, it is difficult to draw direct associations between game time, season time, and player fatigue. If this investigation were to be repeated as a prospective, controlled laboratory study, individual levels of fatigue should be documented and quantified. Such an investigation would still be limited though as fatigue evaluations on an injured player would likely have to be subjective in nature as injury would compromise the integrity and performance of the musculoskeletal system. Alternatively, the establishment of a comprehensive evaluation that could be converted to a quantitative scale for the documentation of relative fatigue in an athlete would be a useful tool to both research and clinical assessment. Similarly, mental fatigue status also went undocumented in the present investigation. Further, while the accuracy of each secondary ACL injury recorded for the present study was verified by two independent observers, it is possible that additional incidences may exist that went undocumented. Identification and inclusion of additional data points always affords the potential to impact the outcomes of statistical analysis.

CONCLUSIONS

The present results indicate that secondary ACL injury incidence was relatively equally distributed with respect to in-game and in-season timing, as there was a lack of timing differences for athletes who participated in Australian Rules Football, Baseball, Basketball, American Football, Hockey, Rugby and Soccer. The hypothesis was supported, which implied that time elapsed within a match or across a season may not be associated with onset of secondary ACL injuries in professional athletes.

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